

### OPERATIONAL AMPLIFIER ARRANGEMENT

The present invention relates to an operational amplifier arrangement, and more particularly operational amplifier arrangements which can be used as line drivers in telecommunication line circuits.

5           Line driver circuits are already known in the art and comprise the classical class-G-based operational amplifiers such as these for instance described in published European Patent Applications 1 024 592 and 1 024 591. Other line driver circuits are based on switching line  
10           drivers such as the one described in the published European Patent Application 1 229 641. Yet other types of line drivers are based on class C-AB architectures, such as these disclosed in published European Patent application 1 220 442 and 1 220 443. Key issues for line drivers in applications such as ADSL , which is the abbreviation of asymmetric digital subscriber line, are the power efficiency, the linearity and the  
15           complexity. Although all types of abovementioned line drivers were conceived such as to optimize these issues, yet there remains a need for improvement of the power efficiency, and linearity, while at the same time keeping the complexity of the operational arrangement as low as possible. This is especially important for very high speed digital  
20           subscriber line applications, hereafter abbreviated with VDSL.

          An object of the present invention is thus to provide an operational amplifier arrangement which is power efficient, linear and simple.

          According to the invention, this object is achieved due to the  
25           fact that said operational amplifier arrangement further includes the features as described in claim 1.

          In this way, a new operational amplifier arrangement architecture is provided having a very good linearity, which is simple and which is very power efficient. Its operation will be described into  
30           detail in the descriptive part of this document, but can be summarized briefly by stating that the non-linear amplifier drives maximum power

to the line with a maximum efficiency, whereby the linear amplifier is correcting the non-linearities caused by this non-linear amplifier, such as cross-over errors, slew rate and other distortions.

A further characteristic feature of the present invention is  
5 described in claim 2.

Thereby power efficiency is further improved by the fact that said non-linear amplifier is working at a reduced supply voltage, such that it is clipping on the high input signal levels. However these additional errors are further corrected by means of the linear amplifier  
10 which is operative at the highest supply voltage level, and which can thus correct these clipping errors.

Further characteristic features of the present invention are shown in claims 3 to 7.

Thereby differential embodiments are provided, for driving  
15 differential signals to two-wire loads. The relationships between corresponding amplifiers, resistors and active back terminating arrangements thereby guarantees further linearity and symmetry of the differential embodiments.

Additional characteristic feature of the present invention are  
20 mentioned in claims 8 and 9.

This further improves the power efficiency of the differential embodiment by means of a more pronounced application of the so-called "active back termination" principle. The active back termination principle is thereby exploited to another resistor level, thereby further  
25 improving the power efficiency while still keeping the same low complexity and good linearity.

Yet other characteristic features of the present invention are stated in claim 10 and 11.

These define additional requirements for operation of the  
30 operational amplifier arrangements, which further enables selecting appropriate resistors and amplifiers.

Another characteristic features of the present invention are described in claims 12 and 13.

These conditions present further restrictions for the resistors in the different embodiments claimed in case these operational  
5 amplifiers need to terminate a series load impedance, such as is the case for a line driver application.

It is to be noticed that the term 'coupled', used in the claims, should not be interpreted as being limitative to direct connections only. Thus, the scope of the expression 'a device A coupled to a device B'  
10 should not be limited to devices or systems wherein an output of device A is directly connected to an input of device B. It means that there exists a path between an output of A and an input of B which may be a path including other devices or means.

It is to be noticed that the term 'comprising', used in the  
15 claims, should not be interpreted as being limitative to the means listed thereafter. Thus, the scope of the expression 'a device comprising means A and B' should not be limited to devices consisting only of components A and B. It means that with respect to the present invention, the only relevant components of the device are A and B.

20 The above and other objects and features of the invention will become more apparent and the invention itself will be best understood by referring to the following description of an embodiment taken in conjunction with the accompanying drawings wherein

Figure 1 gives a schematic of a single-ended embodiment of  
25 an operational amplifier arrangement OAA according to the invention,

Figure 2 schematically depicts a first differential embodiment of an operational amplifier arrangement according to the invention,

Figure 3 depicts another differential embodiment of an operational amplifier arrangement according to the invention,

30 Figure 4 depicts a third differential embodiment of an operational amplifier arrangement according to the invention,

Figure 5 depicts a fourth differential embodiment of an operational amplifier arrangement according to the invention, and

Figure 6 gives an equivalent schematic, depicting the principal operation of the embodiment of Fig. 1 and the embodiments of Figs 2 to 4, according to the invention.

The operational amplifier arrangement OAA depicted in Fig. 1 includes an input terminal IN, an output terminal OUT, and two pairs of supply terminals (not shown on Fig. 1). To this single-ended  
10 embodiment is provided an input voltage from a source  $V_{in}$ , for instance being the signal delivered by the D-A converter in ADSL applications. This input terminal is coupled to the respective input terminals of two amplifiers : a non-linear amplifier A2 and a linear amplifier A3. Such a non-linear amplifier may for instance consist of a class-B amplifier as  
15 indicated in Fig. 1. However, other types of non-linear amplifiers are possible such as switching mode amplifiers , class C or class D amplifiers. In general a very power efficient amplifier will be chosen for this non-linear amplifier in this operational amplifier arrangement. For the linear amplifier A3, class A or AB amplifiers can be used . In a  
20 preferred embodiment, the non-linear amplifier power supply terminals are coupled to one pair of supply terminals of the operational amplifier arrangement, whereas the linear amplifier has power supply terminals which are coupled to the other pair of supply terminals of the operational amplifier arrangement. The supply voltage of the linear  
25 amplifier is thereby higher in amplitude than the supply voltage of the non-linear amplifier. A consequence of this is that high input signals will be clipping to the lower supply voltage levels of the non-linear amplifier, whereas these can yet be amplified nicely by the linear amplifier operating between supply rails of a higher voltage. However in  
30 other embodiments both linear and non-linear amplifiers are operative between the highest supply voltage. Power efficiency of the arrangement

is nevertheless improved for the preferred embodiment whereby the non-linear amplifier operates at a lower supply voltage than the linear amplifier.

The non-linear amplifier A2 has an output terminal OUT A2, and has a first feedback impedance RFA2 coupled between this output terminal OUTA2 and an input terminal IN1A2. Another input terminal IN2A2 of this amplifier is coupled to the ground reference in this single-ended embodiment. The input voltage may be reduced by means of an input resistor RinA2 coupled between the input terminal IN of the arrangement and the first terminal IN1A2.

Similarly, another input resistor RINA3 may be placed in the input path of the linear amplifier A3, thus between the arrangement input terminal IN and a first input terminal IN1A3 of the linear amplifier A3. This linear amplifier similarly has a second input terminal IN2A3, coupled to the ground reference. The output terminal OUTA3 of the linear amplifier is further coupled via a second feedback impedance RFA3, to the first input terminal IN1A3, and also to the output terminal OUTA2 of the non-linear amplifier, by means of an output series impedance R1. OUTA3 is also coupled to the arrangement output terminal OUT, via a terminating impedance Rterm.

The operational amplifier arrangement OAA further includes an active backterminaton arrangement, which, in the embodiment depicted in Fig. 1 simply consists of a feedforward impedance RFABT, coupled between the arrangement output terminal OUT and the second input terminal IN2A3. In another embodiment this active back termination arrangement may consist of an inverter in series with a similar feedforward impedance, both of which are coupled in series between the arrangement output terminal OUT and the first input terminal IN1A3 of the linear amplifier A3.

This feedforward coupling realised by the active backterminaton arrangement is crucial in the operation of the amplifier

arrangement OAA since in this way distorted signals coming from the non-linear amplifier A2, are thereby fed back to an input of the linear amplifier A3 . This linear amplifier thereby amplifies them , but due to the inversion operation of the active back termination also subtracts  
5 them from the total signal as appearing on the summing nodes OUTA3 and OUT. The distorted signal from the non-linear amplifier is thus again corrected by means of the linear amplifier.

It is thereby also mandatory that the gain which is provided by the non-linear amplifier part between IN and OUT , thus including  
10 RINA2, A2, RFA2, R1 and Rterm equals the gain which is provided by the linear amplifier part between IN and OUT, including RINA3, A3, RFA3, RjA3, RFABT and RTERM. Furthermore, it is also mandatory that the part of the output impedance of the arrangement, seen from the output terminal , with only RTERM, A3, RFA3, RFABT concerned, has to be the  
15 same as the part of the output impedance of the arrangement, also seen from the output terminal , but with only RTERM, R1, A2 and RFA2 concerned. The philosophy behind both requirements is that the operational amplifier arrangement consists of two equivalent paths in parallel of which the possible distortions caused by the non-linear  
20 amplifier are corrected by means of the linear one.

The principle of operation of the active back termination arrangement of this embodiment is made clear by means of the equivalent scheme which is depicted in Fig. 6. Following equations hold  
:

25

$$Z_{line} = R1 + R_{term} \quad (1),$$

since  $Z_{line}$  which, in Fig. 6 and in Fig. 1, corresponds to the load impedance, has to be equal to the output impedance  $Z_{out}$  for  
30 appropriately terminating the amplifier arrangement to the line impedance as is mandatory in order to avoid reflections.

Furthermore,

$$V_{outA3} = (V_{in} - (Z_{out}/G) \cdot I_{out} \cdot G) \cdot A3 \quad (2)$$

5               whereby G is the gain of the block consisting of amplifier A1, and impedances  $k \cdot R_{term}$ , and  $k \cdot Z_{line}$ , depicted by means of their resistance values, and A3 here depicts the gain of the linear amplifier A3 and its input resistors and feedback resistors.

10               Since  $Z_{out}/G$  equals  $R_{term}$ , this equation means that the voltage across  $R_{term}$ , being  $I_{out} \cdot R_{term}$ , multiplied by the gain of the block G appears at the input of A3, whereby it is subtracted from the input  $V_{in}$ .

Equation (2) can be further reduced to :

$$15 \quad V_{outA3} = (V_{in} - I_{out} \cdot Z_{out}) \cdot A3 \quad (3)$$

By means of the presence of amplifier A5

$$V_{out} = V_{outA3} \quad (4)$$

20

Such that

$$V_{out} = (V_{in} - I_{out} \cdot Z_{out}) \cdot A3 \quad (5)$$

Equation (5) thus gives the basis for the synthesis of  $Z_{out}$ ,  
25   which needs to be equal to the load impedance, corresponding to the line impedance  $Z_{line}$ , in the case of a line driver. This is performed by the Active back termination arrangement, which, in a very simple embodiment can merely consist of one resistor couplejd between the arrangement output terminal and an input terminal of the linear  
30   amplifier, as was already described for the embodiment of Fig. 1.

Remark that in the scheme depicted in Fig. 6 all amplifiers are inverting amplifiers. This is the reason why an additional inversion, denoted by A4, is to be further included such as to obtain the correct equations. Remark also that the added resistor  $R_{inA3}$  was needed such as to accomplish the summing operation, whereby in the equivalent scheme of Fig. 6 the positive input is kept to the ground reference since the feedback from the output was feeded to the same input terminal to which the input signal was supplied. In the scheme of Fig. 1 the feedback from the output signal on the output terminal OUT was fed to the other input terminal of A3. The presence of amplifier A5 in this equivalent scheme thereby forces the voltage  $V_{outA3}$  to be equal to the output voltage  $V_{out}$ .

Other embodiments of an operational amplifier according to the invention are depicted in Figs. 2 to 5. In Fig. 2 a differential embodiment OAA', including two halves, each of which is similar to the embodiment depicted in Fig. 1, is shown. The first half, coupled to input terminal IN, includes a non-linear amplifier A2, possibly operating at a lower supply voltage than a linear amplifier A3. The linear amplifier has input resistors  $R_{inA3}$ ,  $R_{jA3}$ , and a feedback resistor  $R_{FA3}$ , whereas the non-linear amplifier A2 of the first branch includes has input resistor  $R_{inA2}$ , feedback resistor  $R_{FA2}$ . The output terminal OUTA2 of the non-linear amplifier A2 is coupled via a series impedance R1 to the output terminal OUTA3 of the linear amplifier A3. A terminating impedance  $R_{term}$  is coupled between OUTA3 and a first arrangement output terminal OUT, whereby this first arrangement output terminal is coupled via an active backtermination arrangement, in the embodiment depicted in Fig. 2 simply consisting of a resistor  $R_{FABT}$ , is coupled to an input terminal IN2A3 of the linear amplifier A3.

Similarly, the other half, with input terminal IN', includes as well a linear amplifier A3' and a non-linear amplifier A2'. Linear amplifier A3' has input resistors  $R_{inA3'}$  and  $R_{jA3'}$ , and a feedback



resistance  $R_{FA3'}$ . Non-linear amplifier  $A2'$  has input resistor  $R_{inA2'}$ , and feedback resistor  $R_{FA2'}$ . The single output of  $A2'$ , denoted  $OUTA2'$  is coupled via a second series impedance  $R1'$  to the output terminal  $OUTA3'$  of  $A3'$ . A second terminating impedance  $R_{term}'$  is coupled  
5 between  $OUTA3'$  and the second arrangement output terminal  $OUT'$ , whereas this second arrangement output terminal is coupled to an input terminal of the linear amplifier  $A3'$  via a second active backtermination arrangement  $ABT'$ , in the embodiment depicted in Fig. 2 simply consisting of an impedance  $R_{FABT}'$  coupled between  $OUT'$  and  $IN2A3'$ .

10 For stability, symmetry and linearity reasons both halves are realised using substantially equal devices. Thus  $A2$  and  $A2'$  are chosen as similar amplifiers, as well as  $A3$  and  $A3'$  whereby also the respective input and feedback impedances of the corresponding amplifiers have substantially equal values. Series impedances  $R1$  and  $R1'$  are similar as  
15 well as, terminating impedances  $R_{term}$  and  $R_{term}'$  and active backterminating impedances  $R_{FABT}$  and  $R_{FABT}'$ .

Because of the differentiability, the load impedances in both halves may also be halved with respect to the load impedance in the single ended embodiment. This is the reason why these are depicted by  
20 a load impedance denoted  $Z_{line}/2$  in Fig. 2

The differential operational amplifier arrangement  $OAA''$  depicted in Fig. 3 also includes two arrangement input terminals  $IN1''$  and  $IN2''$ , as well as two arrangement output terminals  $OUT1''$  and  $OUT2''$ , but only includes one amplifier of each type, namely a linear  
25 amplifier  $A3''$ , again operating between the highest supply voltage rails, and a non-linear amplifier  $A2''$  possibly operating at a lower supply voltage.

Both linear and non-linear amplifiers have two input terminals and two output terminals, respectively coupled to the two arrangement  
30 input terminals and the two arrangement output terminals as can be observed from Fig. 3. The arrangement input terminals are thereby

coupled to the linear amplifier input terminals via two respective input resistors, both denoted  $R_{inA3}$  which are also substantially equal because of stability. Similarly two substantially equal input resistors, both denoted  $R_{inA2}$  are coupled between arrangement input terminals and respective non-linear amplifier input terminals. A3 has two similar feedback impedances, both denoted  $R_{FA3}$ . The same holds for A2 having also two similar feedback impedances both denoted  $R_{FA2}$  because they have substantially equal values. Output terminals of A2 are coupled to corresponding output terminals of A3 via respective series impedances, both denoted  $R_1$  because they are similar. With corresponding output terminals is meant that both output terminals of these amplifiers are delivering the same sign of signal at a moment in time. In other words, the positive output terminal of A2 is coupled to the positive output terminal of A3 and vice versa.

The output terminals of A3 are further coupled to the corresponding arrangement output terminals OUT1 and OUT2 via respective terminating impedances, both denoted  $R_{term}$  since these are also similar for symmetry reasons. In the embodiment depicted in Fig. 3, these arrangement output terminals are coupled to the non-corresponding input terminals of the linear amplifiers via respective active back terminating arrangements, in the embodiment depicted in Fig. 3 merely consisting of resistors. In other embodiments however these active back terminating arrangements may again consist of a series coupling of a resistor and an inverter, in which case arrangement output terminals are connected via this type of active back terminating arrangements, to the corresponding input terminals of the linear amplifier A3.

Yet another differential embodiment, OAA10 which shows a lot of resemblance with the one depicted in Fig. 2, is shown in Fig. 4. It again consists of two halves : a first one consisting of a first parallel branch including non-linear amplifier A20, series impedance  $R_{10}$  and

terminating impedance  $R_{term10}$ , and a second parallel branch with linear amplifier A30 and the same terminating impedance  $R_{term10}$ . Both amplifiers may further have feedback such as depicted by RFA20 and RFA30 respectively, as well as input resistance respectively depicted by  
5 RinA20 and RinA30.

The second half of the embodiment of Fig. 4 again consists of two parallel branches : a first one via linear amplifier A31 and a second terminating impedance denoted  $R_{term11}$ , and a second one via non-linear amplifier A21, series impedance R11 and terminating impedance  
10  $R_{term11}$ . As in the first half, the respective amplifiers may have respective input resistors , respectively denoted RinA31 and RinA21, as well as feedback, respectively denoted by RFA31 and RFA21.

The difference with respect to the embodiment depicted in Fig. 2 lies in the coupling of the active back termination arrangements  
15 between the arrangement output terminals and the input terminals of the linear amplifiers . As can be easily observed by comparing both figures, active back terminating resistor RFABT10 is coupled between an arrangement output terminal belonging to one upper half of the arrangement, and an input terminal of the linear amplifier belonging to  
20 the lower half of the arrangement. Similarly, active back terminating resistor RFABT11 is coupled between an arrangement output terminal of the lower half to an input terminal of the linear amplifier of the upper half. This embodiment merely presents an alternative embodiment for realising the active back termination, as compared to the embodiment  
25 of Fig. 2

The embodiment depicted in Fig. 5 is basically similar to the one depicted in Fig. 4, except for the addition of another pair of active backterminating arrangements, in the embodiment of Fig. 5 consisting of resistors RFABT100 and RFABT101 respectively. This second pair of  
30 active back terminating resistors is thereby cross-coupled between an output terminal of a linear amplifier of one half of the arrangement, to

an input terminal of a non-linear amplifier of the other half of the arrangement. Thus, in Fig. 5, output terminal of A31' is coupled to input terminal of A20' via active back terminating resistor RFABT101 while output terminal of A30' is coupled to input terminal of A21' via active  
5 back terminating resistor RFABT100. The presence of a second pair of active backtermination resistors even improves the power effectiveness of the arrangement since this allows to select the series resistances R10' and R11' to be lower compared to the configuration of Fig. 2 . In this case equivalent scheme of Fig. 6 and according formula's are no longer  
10 valid. However the total output impedance of the arrangement OAA10' still needs to be the same to the load impedance .

In Fig. 5 the second active back termination is realised by means of cross-coupling. However in an alternative embodiment the output of the linear amplifier A31 can also be coupled , via a single  
15 resistor, to the "+" input of A21' , or via a series connection of a single resistor and an inverter to the "-" input of A21' for the embodiment depicted in Fig. 5. Similar considerations hold for the active back termination in the upper half of the scheme.

While the principles of the invention have been described  
20 above in connection with specific apparatus, it is to be clearly understood that this description is made only by way of example and not as a limitation on the scope of the invention, as defined in the appended claims.